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AN INVESTIGATION OF LOW-FLOW AUGMENTATION FOR STREAM POLLUTION ABATEMENT

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PROGRESS REPORT

ON AN INVESTIGATION OF

LOW-FLOW AUGMENTATION

FOR

STREAM-POLLUTION ABATEMENT

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and

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U. S. PUBLIC HEALTH SERVICE
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Low-Flow Augmentation Project
Department of Sanitary Engineering and
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The Johns Hopkins University
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The legal, economic, and technical aspects of low-flow regulation for pollution abatement were investigated. The legal phase included a study of public water resources policy, both federal and state, as it affects flow augmentation. Economic evaluation of low-flow augmentation was significant since it requires consideration of alternative methods of pollution abatement. In the technical phase of the study, two new oxygen-sag forumlas were derived. A pair of new formulas for analyzing BOD data were derived and applied to stream observations.

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Report of Progress

on an Investigation of

LOW-FLOW AUGMENTATION FOR STREAM POLLUTION ABATEMENT

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Summary: The project has investigated the legal, economic, and technical aspects of low-flow regulation for pollution abatement. The legal phase included a study of public water resources policy, both Federal and State, as it affects flow augmentation. Legislation, court decrees, and administrative regulations all form policy which controls use of water and storage capacity for this purpose.

Economic evaluation of low-flow augmentation requires consideration of alternative methods of pollution abatement. Past evaluations have considered only cost of advanced stages of treatment as alternative to flow augmentation. Studies have shown that in some rivers, storage of wastes is more economical than storage of water for waste dilution. Methods of evaluating waste lagoons for use in benefits-costs analysis of flow regulation have been derived. A survey of stream-flow criteria for design of waste treatment used by pollution-control agencies in the United States and Canada was carried out as a basis for economic analysis of stream-flow increases for dilution of wastes.

In the technical phase of the study, two new oxygen-sag formulas have been derived. A pair of new formulas for analyzing BOD data were derived and applied to stream observations.

August 31, 1959

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INTRODUCTION

For the past two years an investigation of low-flow augmentation for stream-pollution abatement has been under way in the Department of Sanitary Engineering and Water Resources of The Johns Hopkins University. This project, supported by a research grant from the National Institutes of Health, U. S. Public Health Service, has had as its basic purpose the development of improved methods of evaluating low-flow releases from water-storage impoundments as they affect pollution-abatement programs downstream. The objectives and scope of the investigation have been outlined in a preliminary report (Hill, 1958). This preliminary report was summarized in the Journal of the Division of Sanitary Engineering, Proceedings of the American Society of Civil Engineers (Anon., 1959). The present report describes the progress of the study through August 31, 1959.

The project has been concerned with various aspects of low-flow regulation, some legal, some economic, and some technical. The studies have brought to light several areas of doubt and conflict in the methods used in the past for the analysis of low-flow augmentation. These areas are being defined with the view of promoting research beyond the scope of this project.

This report, necessarily brief, can only outline the findings of the current investigation. As time and resources permit, detailed reports covering specific phases of the study will be prepared.

GENERAL

Simply stated, low-flow augmentation is the release of stored water during dry seasons to increase the natural flows in surface streams. This can be for any of several purposes, including navigation, irrigation, power, water supply, and pollution abatement. The last-named purpose is the subject of the present investigation.

The release of water from multiple-purpose reservoirs for stream sanitation is a beneficial water use which has received relatively little support in the past. It appears that this conservation measure is destined to become more important in the future. Increasing waste loads from growing population centers and expanding industries will inevitably cause stream-pollution problems which, unless solved, will endanger the health, welfare, and economy of large areas, and, indeed, of the entire nation. The increasing importance of these stream-pollution problems demands that all possible avenues of correction be explored thoroughly to provide the best overall solution for each case.

The principles of economy require that any task be accomplished by the cheapest adequate method available. Pollution abatement is no exception. It should be done as economically as possible without sacrificing the water-

quality objectives for other beneficial water uses. As one potential method of pollution abatement, low-flow regulation must receive its share of attention in the study of any pollution problem and its remedies.

If water is to be stored and released for dilution of waste waters, the practice must be sanctioned by public water policy and the courts. The questions of policy and legality have been grouped in the present investigation under the heading of "legal aspects" of low-flow augmentation. In including this phase of the problem, the project does not intend to advise the courts or legislative bodies in matters of low-flow augmention. On the contrary, it is included in recognition of the fact that engineering projects must conform to legal restrictions and legislative fiat. The finer points of water law will be left to the legal profession. This project is concerned only with the more obvious restrictions and requirements concerning the use of water for waste dilution placed on water developers by public laws, court decrees, and published statements of responsible government officials and agencies.

The economic aspects of low-flow augmentation for pollution abatement are all important. Flow regulation for waste dilution is justified only when it can show a favorable economic ratio; that is, the benefits derived from this function of multiple-purpose reservoirs should exceed the incremental cost of the storage capacity and other features that would be necessary. It is also essential to consider the potential monetary damages to pollution-abatement programs when stream flow is regulated for other purposes, such as hydroelectric power development. The economic evaluation of low-flow regulation is dependent upon both legal and technical aspects, as will be discussed later.

The technical aspects of the project are aimed at improving the quantitative evaluation of low-flow augmentation. Procedures are sought which will more accurately determine (1) the quantity of flows required to accomplish a desired degree of pollution abatement, and conversely, (2) the pollution-assimilative capacity that would result from a given increase in stream flow.

LEGAL ASPECTS

Low-flow regulation involves many questions of a legal nature. The use of water for dilution of wastes is competitive with other beneficial uses. Increasing low stream flows may decrease the benefits, for example, of hydroelectric power. The allocation of water use among the various conflicting interests must be based on the legal rights of all users, both present and potential.

Another legal aspect concerns the authority of public agencies engaged in water-resource development to include low-flow regulation as a function of multiple-purpose reservoirs. Existing federal water policy prohibits such inclusinn in government projects unless the United States is reimbursed by the beneficiaries for the cost allocated to low-flow regulation.

Equally as important as the legal questions involved in the provision of pollution-abatement benefits are those concerning the prevention of damages to pollution-abatement programs which may result from impoundments and flow regulation. How does one decide the dividing line between damages and benefits; what minimum flow releases from a storage impoundment will provide break-even conditions for downstream cities and industries which must rely on the flowing stream for ultimate disposal of wastes? These are fundamental questions which must be answered before a reliable economic evaluation of low-flow augmentation can be made.

Public Water Policy--In general, low-flow regulation for pollution abatement is not feasible as a single-purpose water-resource development; where feasible at all, it will be as a part of a multiple-purpose project. These large projects are usually of such magnitude that they can be undertaken only as public projects by a State, regional, or Federal governmental agency. The inclusion of pollution abatement as one of the functions of public multiple-purpose projects depends in large measure on a favorable legal atmosphere. Large scale low-flow regulation will not likely become a widely used method of pollution control without government financial support. The legal atmosphere and public subsidy of low-flow augmentation are matters of public water policy as expressed through legislation, court decrees, and executive actions of legislative, judicial, and executive branches of State and Federal governments. It is therefore pertinent to examine these items as they relate to low-flow augmentation for pollution abatement.

National Water Policy--Wolman (1957) recently decried the absence of any real comprehensive national water policy. The development of water resources by the Federal government has been a collection of piecemeal, uncoordinated actions of Congress and the executive agencies responsible for different phases of water control. Thus the Corps of Engineers deals primarily with flood control and navigation. The Bureau of Reclamation is responsible for irrigation development in the seventeen Western States; it has no responsibilities in the East. The Department of Agriculture administers the small watershed program provided by the Watershed Protection and Flood Prevention Act of 1954 (Hope-Aiken Act). The Federal Power Commission is concerned with hydroelectric power. The Public Health Service of the Department of Health, Education, and Welfare works in the fields of water supply and pollution control. The Fish and Wildlife Service attempts to protect and improve the fisheries resource. The aims and programs of these and other agencies often overlap and, just as often, conflict. Although in a growing number of instances there is a semblance of cooperation among these agencies aimed at comprehensive development of water resources, they have generally acted independently in accordance with their specific responsibilities assigned by Congress.

The national water policy on low-flow augmentation is embodied in a series of documents which have appeared within the last decade. A review of these is informative.

In 1950 the President of the United States established the President's Water Resources Policy Commission and instructed it to study existing Federal legislation and policies in the water resources field. In a letter

to the Chairman of the Commission, the President pointed out that although the Federal Government had played a vital role in developing the Nation's water resources for more than a century, and that during that period our water resources policies has been constantly modified to meet changing needs, it had not always been possible to decide policy changes in the light of broad national objectives. He stated that frequently, new policies had produced inconsistencies in our national water resources policies. He also said that in his judgment it was essential that a comprehensive study and review be made of all existing water resources legislation and policies. He requested the Commission to submit its final report and recommendations not later than December 1, 1950.

In establishing the Commission, the President (Truman, 1950) charged that

> "The President's Water Resources Policy Commission shall study, and make recommendations to the President with respect to, Federal responsibility for and participation in the development, utilization, and conservation of water resources, including related land uses and other public purposes to the extent that they are directly concerned with water resources. The Commission shall give consideration in particular to (a) the extent and character of Federal Government participation in major water-resources programs, (b) an appraisal of the priority of water-resources programs from the standpoint of economic and social need, (c) criteria and standards for evaluating the feasibility of water-resources projects, and (d) desirable legislation or changes in existing legislation relating to the development, utilization, and conservation of water resources."

All executive departments and agencies of the Federal Government were directed to cooperate with the Commission in its study.

The President's Water Resources Policy Commission transmitted its report to the President in December, 1950 (Cooke et al, 1950). The lengthy report has relatively little to say about water pollution and its control. This was to be expected in a study of past Federal activity in the water resources field--the Federal Water Pollution Control Act was passed in 1948, only two years before the Commission's report was prepared. In contrast, Federal participation in another phase of water development, irrigation, dated back to 1902 when the Reclamation Act established the irrigation program in the West. Nevertheless, study of the 1950 report does provide an insight into the current policies of Federal agencies toward low-flow augmentation.

Part of the report of the President's Commission was devoted to reviews of typical projects which had been constructed earlier by Federal agencies. These reviews were prepared by the agencies concerned. Several of the projects reviewed were reported to have provided benefits to pollution abatement from low-flow augmentation.

In the review of Corps of Engineers projects, two were mentioned as having pollution control features. These were the Tygart Reservoir, in West Virginia, and the Cottage Grove Dam, in Oregon. Tygart Reservoir, on a tributary of the Monongahela River, augments dry-weather flows in the Monongahela, which receives pollution from the heavily industrialized area of Pittsburgh. It was stated that benefits realized from pollution control were much greater than originally anticipated. This project, completed in 1938, is one of the earliest projects in which consideration was given to pollution-abatement benefits. However, the low-flow augmentation provided by this project was primarily for improvement of navigation, so that the pollution-abatement benefits were more or less incidental.

Cottage Grove Dam is on Coast Fork, Willamette River in Oregon. Authorized in 1938 and completed in 1942, the dam provided flood control and increased low water flows in the interests of navigation, irrigation, power production, and stream purification.

These two Corps of Engineers projects indicate that agency's recognition of low-flow augmentation for pollution-abatement as a potentially beneficial function of multiple-purpose water developments.

The Fish and Wildlife Service reviewed only one project in the President's Water Resources Policy Commission report. The report describes the Souris River wildlife-refuge development in North Dakota. Primarily for the benefit of water fowl, storage of flood water and release during dry periods is reported to provide water for sanitary flushing and disposal of municipal wastes for communities on the river below the reservoir.

Though not a construction agency, the Public Health Service is the principal Federal agency concerned with water pollution control, charged with the administration of the Federal Water Pollution Control Act of 1948. In this capacity, the Public Health Service submitted a review of projects constructed by other agencies, both private and public, as they related to stream pollution and control. In its review, presented in the President's Commission report, the Service pointed out that "... increasing low flow in polluted streams is an important contribution to the solution of water pollution problems." It also cautioned that low-flow augmentation is not a complete solution, and that at least primary sedimentation of liquid wastes is needed to remove sludge deposits, floating sewage solids, and scum.

The Public Health Service cited the Mahoning River in Ohio as an example of low-flow augmentation benefits to pollution control. There, flow regulation by Milton Reservoir, constructed by private interests, and by Berlin and Mosquito Creek Reservoirs, constructed by the Corps of Engineers, was credited with improvement of the stream near Youngstown. Whereas control of pollution would have been technically and economically impractical with known treatment methods before regulation, the increased low flows made correction feasible.

On the negative side, the Public Health Service reported that Hastings Dam on the Mississippi River below Minneapolis and St. Paul had aggravated the control of pollution from those two cities. Because a section of the

river was changed from a running stream with relatively good self-purification characteristics to a slow-moving, navigable waterway, the sewage discharged into the river needed about 25 per cent greater treatment than would have been the case without the dam.

This same detrimental effect of canalization was reported for the Ohio River between Cincinnati and Louisville. It was stated that this navigation project tended to complicate the problems associated with sewage disposal, nuisance control, water treatment, and preservation of public health.

The Public Health Service's review of water resources development projects indicated that this agency, though it had no direct responsibility in the planning and construction of these projects at that time, was already well aware of potential benefits and damages to pollution-abatement programs resulting from water-control projects.

The Federal Power Commission reported that it does not construct or operate power projects, but issues licences to public and private agencies to construct and operate such projects affecting streams over which Congress has jurisdiction, affecting Federal lands, and at Government dams and reservoirs. In reviewing several licensed projects, the Federal Power Commission made no mention of pollution abatement, but stated that licenses are issued only after a finding by the Commission that the project is adequate to make the best use of the resources and is adapted to a comprehensive plan of development of the region's resources. Presumably, this policy would allow a finding that a project should include low-flow augmentation for pollution abatement where this function would be the best use of a portion of the project. Certainly the "comprehensive plan of development," to which the project must be adapted, would include at the least consideration of low-flow regulation, if truly comprehensive.

Several of the agencies which submitted reviews of typical projects, notably the Bureau of Reclamation and the Department of Agriculture, made no mention of pollution abatement in connection with their programs of water resource development. This probably reflects the absence, at that time, of any specific authority or instructions from Congress concerning pollution abatement as a function of multiple-purpose water projects under their supervision and control.

The President's Water Resources Policy Commission, in its own summary of the reviews submitted by the various Federal agencies, noted that

> "In some cases, it has been found that aggravated pollution conditions can be abated most economically by primary sewage treatment plants augmented by increased low flow of rivers with upstream storage reservoirs to increase the low flow of rivers..."

In its report submitted to the President, the Policy Commission outlined a recommended water policy for the Nation. Two of the principles set forth are quite pertinent to this study, as follows:

"Pollution control should be considered in the planning of river basin programs. It should be recognized as a major contribution to the Nation's objectives in the fields of water supply, recreation, and fish and wildlife..."

and

"Multiple-purpose reservoirs should, as far as consonant with other major purposes, be planned and operated so as not to aggravate but to contribute to the control of pollution. This should include regulation of releases of water to make fullest use of the stream's potential self-purification capacity, with advance determination of the schedule of releases to permit proper classification of the stream by the Public Health Service for pollution control purposes."

These recommendations were significant in that they evidenced official recognition of the need to consider pollution abatement as a potential function of all multiple-purpose river developments. The second recommendation quoted also shows official concern for the potential damage to pollution-abatement programs that might result from reservoir projects for other purposes.

The report of the President's Water Resources Policy Commission was not the first attempt to establish a unified comprehensive water policy. However, it was a significant recent milestone in the slow evolutionary process of developing the national water policy which dates back more than half a century. It was especially significant in relation to low-flow augmentation in that it recognized that pollution control was essential in water resources development, and that low-flow regulation was a potential means of pollution abatement. Although the Policy Commission was a temporary instrument of the executive branch of the Federal Government; and therefore its recommendations had no binding effect on the Congress, the report undoubtedly has influenced Congressional thinking and has certainly influenced the executive agencies responsible for water resources development.

The year 1950 saw another development in the evolution of Federal water policy. In that year, the Federal Inter-Agency River Basin Committee published a report on the economic evalution of projects (F.I.A.R.B.C., 1950). The report outlined the existing practices of the agencies represented on the Committee and recommended mutually acceptable procedures for evaluating benefits and costs of water development projects. The member agencies included, at that time: the Corps of Engineers of the War Department, the Bureau of Reclamation of the Department of the Interior, the Department of Commerce, the Department of Agriculture, and the Federal Power Commission. In this study of low-flow augmentation, it is pertinent to note that the Federal Security Agency or its constituent agency responsible for pollution control, the Public Health Service, was not represented on the Inter-Agency Committee. This of course is explained by the fact that the Inter-Agency Committee and its Subcommittee on Benefits and Costs, which prepared the 1950 report, were both formed before the enactment of

the Federal Water Pollution Control Act of 1948. (The Department of Health, Education, and Welfare, successor to the Federal Security Agency, has since become a member of the Inter-Agency Committee.)

From the viewpoint of this study, the 1950 Inter-Agency Committee's report on economic evaluation is of interest primarily because it indicates the growing attempts to unify public water policy and procedures of the Federal Government, at least within the executive branch. The report, in reviewing the past practices of the various agencies, hardly mentions pollution control, but the review of the general bases for measuring all benefits and costs would be applicable to pollution-abatement. The report stated that there was wide variation in the practices of measuring major benefits among the several agencies, but that

> "The relatively minor differences in the measurement practices for other benefits, such as water supply, sedimentation control, pollution abatement, etc., do not usually result in appreciable differences in project benefit estimates."

However, a comparison of the current (1950) practices of the participating agencies presented in a table in the report did reveal significant differences in the methods used for measuring benefits from pollution abatement. The methods were summarized for each agency as follows:

Corps of Engineers' practice on navigation, flood control, and multiple-purpose projects--

Benefits measured by the cost of providing the most economical alternative methods of waste treatment or disposal, or reduction in maintenance and operating costs where alternative methods of pollution abatement are not economical.

Department of Agriculture practice on watershed treatment programs--

Benefits usually not evaluated in monetary terms.

Department of the Interior practice on irrigation and multiple-purpose projects of the Bureau of Reclamation--

Same practice as that described for Corps of Engineers.

Federal Power Commission practice on Federal multiple-purpose projects involving power development--

Estimates of benefits obtained from agency responsible for project or, when necessary, independent estimates made by similar methods.

Another milestone in the development of Federal water policy was reached in December 1952 with the issue of the Bureau of the Budget's Circular A-47 (Bureau of the Budget, 1952). This document, sent to the heads of Federal executive agencies having responsibilites for development of water and related land resources programs, was

> "...designed to set forth the standards and procedures which will be used by the Executive Office of the President in

reviewing proposed water resources project reports and budget estimates to initiate construction of such projects..."

The directive, still in effect, covers all Federal programs or projects for the conservation, development, or use of water and related land resources. It prescribes procedures and definitions of terms for use in reports submitted in support of budget estimates and legislation covering such programs or projects. The definitions of particular interest in this study of pollution abatement are quoted below:

"Definitions. For the purposes of this circular:

'Benefits,' as used for purposes of evaluation of proposed programs or projects, means all the identifiable gains, assets, or values, whether in goods, services, or intangibles, whether primary or secondary, and whether measurable in monetary or nonmonetary terms, which would result from the construction, operation, or maintenance of a program or project.

'Primary benefits' means the identifiable gains, assets, or values directly resulting from any program or project.

'Secondary benefits' means identifiable gains, assets, or values other than primary benefits of a program or project which are properly creditable to the program or project.

'Economic costs,' as used for purposes of evaluation of proposed programs and projects, means all the financial costs of the program or project except investigating, surveying and planning costs incurred prior to authorization; and all the other identifiable expenses, losses, and liabilities, whether in goods, services, or intangibles, whether direct or induced, and whether measurable in monetary or nonmonetary terms, which are incurred as a result of constructing, operating, or maintaining a program or project.

'Financial costs' means all the monetary outlays made in connection with a program or project and interest costs connected therewith; i.e., the construction costs, the operation and maintenance costs, and interest on the unliquidated balance of the reimbursable construction costs. When applied to allocations made to irrigation for repayment purposes under paragraphs 7a and 18b, 'financial costs' shall not include interest on the irrigation constructions costs.

'Construction costs' means expenditures (amount paid and payable) for the initial project construction and the net replacements and additions of significant units thereof, including contract work, materials and supplies, labor, and use of equipment; acquisition of lands, easements, rights-of-way, and water rights; costs of relocating facilities and the settle-

ment of damage claims; interest during construction; any capital expenditures for protection of public health, for preventing loss of or damages to recreation, fish and wildlife and mineral resources, and scenic, archeological, and historical values; any capital expenditures for the replacement of recreation and fish and wildlife resources damaged or destroyed by the project; and all other amounts of expenditures specifically applicable to the investigations, surveys, plans, designs, and construction of the project. When applied to allocations made to irrigation for repayment purposes under paragraphs 7a and 18b, 'construction costs' shall not include interest during construction on the costs allocated to irrigation.

'Operation and maintence costs' means those expenditures for materials and supplies, labor, necessary services, equipment and operating facility use, and an appropriate portion of engineering, supervision and general expenses of the agency which are needed to operate a project once constructed and to make repairs, minor additions and replacements, and otherwise to maintain the project in sound operating condition for a maximum economic life. This includes any expenditures of the project, other than capital expenditures, for protection of public health, for preventing loss of or damages to recreation and fish and wildlife resources, and scenic, archeological and historical values; and any expenditures of the project, other than capital expenditures, for the replacement of recreation and fish and wildlife resources damaged or destroyed by the project."

Circular A-47 directs that the economic evaluation of the program or project shall include an estimate of the primary benefits. Among those primary benefits are those resulting from...

"...the reduction in the cost of pollution abatement by stream flow augmentation. Such benefits should be calculated as the residual benefits possible after allowing for all direct measures to control pollution at the source that would normally be required or considered necessary by the public health authorities concerned."

Circular A-47 also specifies those items which shall or may be included in the evaluation of the costs of a program or project. Items of interest here are quoted from paragraph 9 of the circular as follows:

"The evaluation...shall include an estimate of the total construction costs and the total operation and maintenance costs of the program or project, whether such costs are incurred by the Federal Government, State and local governments, or private interests.

"Such an evaluation shall also include a statement of economic costs expected to be induced by the program or project, such as the costs of:

a. ...

b. Decreased value of ... water quantity or quality, and other water or related land resources, where not reflected in market values.

c. Rectifying adverse effects upon sanitation, transportation, ...

d. Unprevented and uncompensated losses of or damages to fish and wildlife resources; recreational resources; and scenic, archeological or historical value."

The circular states that the

"...evaluation shall also include an appraisal of other detriments to the general welfare, whether or not they can be measured in monetary terms, and the groups which will suffer any substantial injury should be identified so far as feasible."

Circular A-47 lists those purposes to which costs may be allocated. These are:

1. Flood control
2. Reclamation
3. Navigation
4. Watershed management
5. Electric power and energy
6. Domestic, municipal, or industrial water supply
7. Recreational development
8. Fish and wildlife development
9. Pollution control or abatement

This directive of the Bureau of the Budget indicates that pollution abatement is a proper and allowable function of multiple-purpose water developments. However, Circular A-47 specifically states that:

"Allocation of costs to pollution control or abatement shall be limited to those costs for that purpose which are to be fully reimbursed by the States, local governments, districts, or other interests concerned, including other Federal establishments."

Circular A-47 therefore makes it clear that, as of 1952, the official policy of the executive branch of the Federal Government was that low-flow augmentation for pollution-abatement benefits could not be provided by a Federal project on a nonreimbursable basis. This specific policy appears to have been based primarily on the general policy expressed in the Water Pollution Control Act of 1948, as follows:

"...it is hereby declared to be the policy of Congress to recognize, preserve, and protect the primary responsibilities and rights of the States in controlling water pollution..."

On the other hand, Circular A-47 also makes it clear that damages to pollution-abatement programs are to be considered in the evaluation of water-resources projects and programs.

More recent documents reaffirm the Federal policy of requiring reimbursement for any pollution-abatement benefits provided by Government financed water projects. In 1954 the President established the Cabinet Committee on Water Resources Policy, subsequently redesignated the Presidential Advisory Committee on Water Resources Policy. This committee was composed of the Secretaries of Agriculture, Defense, and Interior. The latter served as chairman. The Secretary of Commerce, the Secretary of Health, Education, and Welfare, and the Director of the Bureau of the Budget participated on an ad hoc basis by direction of the President. The Committee was instructed to undertake an extensive review of all aspects of water resources policy, and to submit recommendations for the strengthening, clarification, and modernization of water policies.

The Presidential Advisory Committee on Water Resources Policy submitted its report to the President in December 1955 (McKay et al, 1955). In its report, the Committee recommended...

"That, as a general policy, all interests participate in the cost of water resources development projects in accordance with the measure of their benefits; that the Federal government assume the cost of that part of projects where benefits are national and widespread and beneficiaries are not readily identifiable; that power and municipal and industrial water users pay the full cost of development; that where projects are primarily local, and the beneficiaries are clearly identifiable, the Federal Government's contribution should be limited, with non-Federal interests bearing a substantial portion of the construction costs of the project as well as the replacement, maintenance, and operation costs; and that under certain conditions the Federal Government may bear a higher proportion of the costs..."

Elsewhere, the report states:

"Furthermore, the Committee believes that those persons and areas receiving direct benefits from water development projects should contribute toward their cost."

Still elsewhere, the Advisory Committee had this to say:

"Just as a sound national policy should provide for joint participation of Federal and non-Federal interests in the planning of water resources, by the same token it should provide for an equitable sharing of costs. As a general

principle, the share of the costs to be borne by the beneficiaries should be proportionate to the benefits received."

and:

"Identifiable beneficiaries should pay an appropriate share of the cost of projects."

and:

"The Committee endorses the established policy of primary State responsibility for controlling water pollution at its source. This is a traditional State responsibility and should continue..."

The report of the Presidential Advisory Committee was submitted to the Congress by the President in January 1956. In his letter of transmittal, the President commended the fundamental purposes and objectives of the report and recommended that the Congress give prompt attention to its proposals.

Taken together, Circular A-47 and the Advisory Committee's report leave little doubt as to the policy of the executive branch on low-flow augmentation for stream-pollution abatement. Briefly, that policy is that pollution abatement should always be considered in the planning of water resource projects, but this function should be a part of any project only if the cost is borne by other than the Federal Government.

By way of example, a recent Corps of Engineers report on a proposed new project in the Mahoning River Basin recommended the inclusion of low-flow augmentation for water supply and pollution abatement (House Document No. 191, 85th Congress, 1st Session). The report calls for increasing the presently regulated flows by increments varying from 40 cubic feet per second (cfs.) in the winter to 65 cfs. in the summer. The monetary benefits from this additional flow regulation were estimated by the Public Health Service at $87,700 annually for abatement of organic pollution and $160,200 for water supply improvements. The total benefits from the incremental flow increase of 65 cfs. or less was thus $247,900 annually. This large monetary benefit from low-flow augmentation results from the heavy concentration of industry and population in the Mahoning River area, especially at Youngstown.

In its report on the Mahoning River Project, the Corps of Engineers recommended that local interests be required to pay the full costs of the proposed low-flow augmentation, amounting to $5,729,000. This was 49.6 per cent of the total project costs. The remainder of the project costs were allocated to flood control. The Corps of Engineers' report states:

"The standards and procedures at present governing the apportionment of costs of reservoir projects being recommended for authorization generally call for all costs allocated to flood control to be borne by the United States...These present standards and

procedures also call for apportionment to local interest of all costs allocated to low-flow augmentation."

The existing water policy of the executive branch of the Federal Government as related to low-flow augmentation for pollution abatement is very well expressed in the documents just reviewed. However, none of these documents has the force of law and does not limit the Congress in its function of legislating and budgeting for water-resource development. Nevertheless, the Executive policy is certain to influence the deliberations of Congressional committees considering bills for authorization of water-development programs or projects. Furthermore, if the Congress ever does enact legislation creating a comprehensive national water policy, the Executive documents will serve as guides.

The Congress has not yet seen fit to follow the 1950 recommendations of The President's Water Resources Policy Commission and the Presidential Advisory Committee on Water Resources Policy; the Congress has not yet enacted any comprehensive legislation on water-resources policy. Nevertheless, a start toward a Congressional water policy has been made in the form of a Senate resolution. The document referred to is Senate Resolution 148 (85th Congress, 1st Session), which was adopted in 1957.

Senate Resolution 148 purports to provide for improvements in the procedures for evaluation of land and water resource projects. The resolution requests that the executive agencies responsible for preparation of reports relative to authorization of projects furnish certain information considered necessary for project evaluation. It calls for a description and, to the extent possible, computation or other evaluation of indirect and intangible net benefits including, among others, abatement of pollution (including salinity), and maintenance and enhancement of the agricultural, commercial, and industrial economy of the area affected. The resolution also calls for information on the physical feasibility and costs of providing capacity in project works for current needs and future uses that may reasonably be anticipated to develop during the useful life of such project works.

Compliance with these portions of Senate Resolution 148 would require the agencies preparing reports to consider, among other beneficial water uses, low-flow augmentation for pollution abatement. The reference to future needs is believed to be especially significant, as many authorities foresee the need of low-flow regulation as the only economically feasible means of water-quality improvement in situations where the highest practicable degree of waste treatment will still be inadequate.

The decision regarding inclusion of storage capacity for long-term future water requirements is a perplexing one. Conservationists generally recognize that development of scarce reservoir sites for less than maximum potential capacity may result in long-term waste of that potential which eventually will be needed. However, future needs must be weighed carefully against the burden of cost for unused capacity during the period before the anticipated demand develops.

The committee report on Senate Resolution 148 (Senate Report, 1957) stated that there is a tendency for Congress to lose its responsibility for determining the land and water resources program, and that executive definition and limitation of the program have restricted the proposed projects presented to the Congress for authorization. The Committee on Interior and Insular Affairs and the Committee on Public Works, which jointly submitted the report, apparently feel that more projects are worthy of Congressional consideration than have passed the criteria established by the executive agencies.

Much of the information called for by Senate Resolution 148 is also required by the Bureau of the Budget as outlined in Circular A-47. The resolution indicates a desire of the Senate to accelerate the water development program of the Federal Government. The resolution and the accompanying committee report appear to favor more liberal procedures and criteria for economic evaluation of projects. This attitude, if it persists, should have a positive effect on development of water for all beneficial purposes, including pollution abatement.

In any discussion of water policy as it affects low-flow augmentation, mention must be made of a recent effort by the Congress to change the existing Federal policy requiring reimbursement for pollution-abatement benefits provided by Federal water projects. In the annual omnibus bill on rivers and harbors and flood-control projects (85th Congress, 2nd Session), Congress included a section which would authorize the inclusion of storage in Corps of Engineers' reservoir projects for regulation of low flows downstream without reimbursement. The portion of the bill, S.497, pertaining to low-flow regulation is as follows:

Section 205(b)

> "In prosecuting plans and projects for navigation, flood control, and allied purposes heretofore or hereafter authorized, storage may be included in any reservoir project constructed or to be constructed by the Corps of Engineers without reimbursement to increase low flows downstream to the extent warranted at that time, or anticipated to be warranted during the economic life of the project, by widespread, general, and nonexclusive benefits from such increases in low flows."

This section, if it had been enacted, would have resulted in a departure from the established Federal policy which has called for payment of costs by the beneficiaries of low-flow regulation.

In a letter submitted to the Chairman of the Senate Committee on Public Works, the Bureau of the Budget expressed opposition to the provision of nonreimbursable pollution-abatement benefits from low-flow augmentation. The Bureau's letter, quoted in the Committee report on S.497 (Senate Report, 1957), states in part as follows:

> "With regard to section 205, we believe that in line with the Water Pollution Control Act, pollution abatement should be

regarded as primarily a responsibility of States and local interests. We also believe that storage for low-flow regulations should be reimbursable under the same terms as storage for water supply. We, therefore, recommend that section 205 be amended to make clear that low-flow regulation for sewage dilution shall not be used as a substitute for treatment works required under standards established by States under the Water Pollution Control Act and to provide that the costs of storage for low-flow regulation for pollution abatement or water supply be reimbursable..."

The Bureau of the Budget is part of the Executive Office of the President, so it can be assumed that the above-quoted portion of the Bureau's letter represented the president's view on this subject at that time (February 25, 1957).

Senate Bill S.497 was eventually passed by the Senate on March 28, 1957, and by the House of Representatives on March 11, 1958. However, the bill was vetoed by the President. In his veto message, dated April 15, 1958, the President specifically objected to the provision in the omnibus bill for authorization of nonreimbursable low-flow augmentation. The portion of the veto message pertaining to low-flow regulation is quoted below:

"...In particular I believe the bill is defective for the following reasons:

"...It would authorize, in reservoir projects of the Corps of Engineers and the Bureau of Reclamation, the inclusion without reimbursement of water storage for increasing the flow in times of low water; even though the beneficiaries of such works may be clearly identifiable. It would also authorize the inclusion of municipal and industrial water-supply storage in such projects without providing adequate standards for payment of an appropriate share of the basic costs by local interests. In addition, there has been insufficient exploration of the complex legal implications of these ambigous provisions as affecting water rights. It is my firm conviction that such important substantive changes affecting water resources policy and costs should be made, if at all, only after full, independent consideration not related to an omnibus authorization bill. The Secretary of the Army has previously made suggestions for acceptable legislation on this subject."

Following the President's veto, Senate Bill S.497 was eventually redrafted without the section on low-flow augmentation. The new bill was passed by the Congress and approved by the President (Public Law 500, 85th Congress, 2nd Session).

With the failure of S.497 to be enacted into law, the Federal water policy remains against the provision of low-flow augmentation on a non-

reimbursable basis. However, this policy does not preclude low-flow regulation as a function of Federal multiple-purpose projects, if financial support can be obtained from sources other than the Government.

State Water Policy--Inasmuch as the States have the primary responsibility for pollution control, as recognized in the Federal Water Pollution Control Act, the policy adopted by any State agency on low-flow augmentation for pollution abatement will be all important in deciding the extent that water will be used for this purpose in that State. For this reason, the Low-Flow Project has undertaken a review of State water policies in relation to low-flow augmentation. This review is in its early stages, so that relatively little can be reported at this time.

Preliminary findings indicate that the States have not generally taken any position on low-flow augmentation for pollution abatement. The States have been no more inclined to adopt comprehensive water-resources policies than has the Federal Government. Documented water policy in the States appears to be largely nonexistent. However, there has been an awakening in most of the States in recent years to the need for conserving water resources for all beneficial uses. Many committees, boards, and other study groups have been established and assigned the task of developing comprehensive legislation in the water field. Thus the stage appears to be set for the rapid evolution of definite public water policy in many of the States. Several States have already written general policy statements into water laws, but few of these can be considered comprehensive.

In 1931 the Maryland legislature established a Water Resources Commission and charged it with the duty of reviewing the water resources of the State of Maryland and of formulating a plan for development and control of water resources. The Commission issued a report of its review in 1933 (Wolman et al, 1933). The report took cognizance of the value and need for the regulation of stream flow for various purposes, including the dilution and disposal of wastes. The report states:

> "Where stream flows during dry weather do not suffice for public and industrial water supply or water power requirements, for dilution of sewage or industrial wastes, or for navigation, the construction of impounding reservoirs, in which the water level is kept as high as possible, and from which such quantities of water are drawn as will meet the daily dry weather demands, proves necessary..." (Emphasis added.)

The Commission also recognized the potential effect of other water uses on pollution assimilation. As an example, it pointed out that:

> "A number of industrial and power enterprises make rather extensive use of the Patapsco River. With the entrance of Baltimore City into the field as a prospective consumer of this river's water, lower riparian interests, as well as sewage disposal facilities which the stream might afford, will suffer unless a judiciously regulated flow is maintained."

In 1933, Maryland passed its Water Resources Law, the purpose of which is "...to conserve, protect and utilize the water resources of the State, in accordance with the best interests of the people of Maryland." The law declares that it is the policy of the State to control the appropriation and use of both surface and underground waters.

Maryland is represented among the few States where low-flow augmentation is accomplished specifically for pollution abatement. The Stony River Dam, owned by a paper manufacturing company, is located on a tributary of the Potomac River in West Virginia. The project provides an auxilliary water supply for the company's mill at Luke, Maryland, on the North Branch of the Potomac River. It also provides dilution of wastes in the North Branch and in the main stem of the Potomac River. Another dam in the same area, the Savage River Project, was designed for the same purposes. Construction on this dam was initiated in 1936 as a WPA* project, but was interrupted by World War II. It was completed as a Corps of Engineers project with the added purpose of flood control. With the Stony River and Savage River Dams in operation, the flow in the North Branch at Luke, Maryland, is sustained at a minimum of 93 cfs. It can be assumed from these examples that Maryland water policy does not prohibit the storage and use of water for increasing low flows to dilute wastes.

Mississippi has recently passed a law providing for State control of the use of water resources, with a gradual transition from the riparian doctrine of water rights to the doctrine of appropriation (Mississippi Laws, 1956). A significant aspect of the Mississippi law, from the viewpoint of flow regulation for pollution control, is the establishment of a definite criterion for minimum flows in surface streams with the provision that the "established average minimum flow" cannot be appropriated. The law provides for appropriation of water in excess of the legally defined minimum flow for beneficial uses. "Beneficial use" is defined in the law as "the application of water to a useful purpose that inures to the benefit of the water user and subject to his dominion and control but does not include the waste of water." Presumably, the use of water for increasing stream flow to abate pollution would be a "beneficial use." This presumption is supported by a State report (Mississippi Water Resources Policy Commission, 1955) which preceded and recommended the 1956 law. In this report the problem of stream pollution control was emphasized. In discussing remedies, the report stated:

> "It is possible that the problem can be solved in part by upstream storage and by more intensive application of soil conservation measures, and resulting improved stream flow."

On the other hand, the law specifically states, in connection with vested water rights not to be affected by the new law, that:

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* Works Progress Administration

> "...it is not the intent of this act that any person making use of any watercourse for waste disposal or in pollution abatement, on the effective date of this act, shall be construed as having any vested right to pollute the waters of the water course."

This section of the law tends to indicate that pollution abatement by dilution might not be considered a legitimate beneficial use of water.

The Mississippi law does recognize the possibility that excessive appropriation and diversion of water from a stream would cause damage to pollution-abatement programs. It specifically prohibits any appropriation that will impair the effect of stream standards set under the State's pollution-control laws based on the minimum average flow of a stream.

In Texas, priorities for beneficial water use are established by law (Texas Board of Water Engineers, 1956). The order of priority is:

1. domestic and municipal uses,
2. manufacturing processes,
3. irrigation,
4. mining and recovery of minerals,
5. hydroelectric power,
6. navigation, and
7. recreation and pleasure.

For purposes of this study, the omission of "pollution abatement" or "waste disposal" from the above list is significant. However, "municipal uses" are generally interpreted in many States as including waste disposal, and might be so interpreted in Texas, although this view is less widely accepted in the relatively arid West than in the more humid Eastern States.

The Texas Board of Water Engineers pointed out in its 1956 report that one of the most serious problems of the State was the lack of adequate conservation storage capacity for flood waters. The Board noted that the Federal agencies could not, under the existing Federal water policies, provide conservation storage in their flood control program unless the Government is reimbursed by State or local interests. It also suggested that State legislation providing for such cooperation would allow the available and limited dam sites to be developed for water conservation instead of for the single purpose of flood control. The intended meaning of "conservation" and whether it includes low-flow augmentation for pollution abatement is not made clear in the report.

Pennsylvania has not only recognized flow regulation as a means of waste control, but has actually carried out a State-financed project which includes low-flow augmentation as a function. According to Ryder (1938), Pymatuning Reservoir was built in northwestern Pennsylvania at a cost of about $3,700,000 for the primary purpose of increasing low flows in the Shenango and Beaver Rivers. Ryder stated that because of the increased low flows, the Pennsylvania Department of Health reduced

the degree of sewage treatment it had previously prescribed for all municipalities discharging wastes into these rivers.

The foregoing discussion of public water policy can be summed up briefly. Both Federal and State agencies and officials generally have recognized low-flow augmentation for pollution abatement as a beneficial use of water. Federal water policy calls for consideration of pollution abatement as a potential function of Government projects, but prohibits the development of water resources for this purpose at Federal expense. The policy of the various States is not nearly so well defined, but in general, the limited number of policy statements on water resources indicate recognition of this water use and appear to encourage or at least allow it. However, few instances of State financial support of low-flow augmentation projects can be found.

Design Criteria for Waste Treatment--Another important legal aspect of low-flow augmentation involves the question of setting the base condition for purposes of evaluating the effects of flow regulation on pollution-abatement programs. Flow regulation which provides a minimum sustained rate of waste-assimilative capacity less than that available in the unregulated stream would result in damage to pollution abatement. Such flow regulation would increase the need for waste treatment. On the other hand, controlled flows which provide increased critical waste capacity of a stream, so that treatment requirements would be reduced, would benefit the pollution-abatement program. Between these two conditions of flow regulation lies the break-even or "no-damage" point which neither helps nor hinders pollution abatement.

The no-damage condition must be established for any river development project before an economic evaluation of the effects of the project on pollution abatement can be made. The logical starting point is to determine the design waste-assimilative capacity of the unregulated river, that is, the condition for which waste treatment or other pollution-abatement facilities would be designed in the absence of flow regulation. Establishing this base condition should be simple in theory, but it involves many questions of a policy nature.

It has been noted previously that the States retain the primary responsibilities and rights in the field of pollution control. Therefore, the setting of waste-treatment requirements is the prerogative of the State. The difficulty, from the standpoint of evaluating low-flow augmentation, is that the criteria used for determining the design waste capacity of streams vary from State to State. In fact, many States have no specific design criteria.

Early in this investigation, in recognition of the fact that the design flow of a stream is generally the principal factor controlling its design waste-assimilative capacity, a survey of the stream-flow criteria used for the design of waste-treatment works was undertaken. A questionnaire was sent to all water pollution control agencies in the

United States and Canada. Replies have been received from most of these and are being studied and summarized for presentation in a separate report. In preparing the summaries, information available in the literature was used to supplement the replies received from the agencies. A sample summary, for the State of Mississippi, is appended to this report.

It is hoped that the report of the survey of past and current practices in the use of stream-flow criteria for the determination of waste-treatment requirements will serve as a guide in evaluations of low-flow regulation. It is also hoped that the review of stream-flow design criteria will show the need for more general use of such criteria, not only in the evaluation of flow regulation, but also in the determination of the ability of unregulated streams to assimilate pollution.

Stream Standards versus Effluent Standards--It should be noted that all pollution control agencies do not base waste-treatment design on stream-flow criteria. Many State regulatory bodies prefer to specify the allowable quality of waste effluents before they are discharged to surface streams. The principal advantage of these so-called effluent standards is their relative simplicity from an administrative viewpoint. The disadvantage of effluent standards is that they do not allow full use of the natural self-purification capacity of the streams, or in some cases, may result in overloading that capacity. It appears that only by the use of standards based on water quality in the stream itself would it be possible to prove stream pollution in a legal sense. However, it must be recognized that effluent standards are widely used, and abatement orders based on these standards have been upheld by the courts in many cases.

Stream standards call for maintenance of concentrations of waste components in the stream below certain specified limits. The allowable stream concentrations are normally established at values which, in the judgment of the control agency, will not cause damage to other reasonable and necessary water uses. The principle advantage of stream standards over effluent standards is that the full assimilative capacity of the stream can be utilized, thus minimizing the cost of waste treatment facilities. A corollary advantage is that low-flow augmentation can be used when economically justified to dilute treated wastes and thereby reduce the degree--and cost--of treatment required. The primary disadvantage of stream standards is that their enforcement is generally more difficult, requiring field observations of stream-water quality. However, it should be obvious that in the final analysis, water uses other than waste carriage depend on water quality in the stream and not on the quality of waste effluents.

Low-Flow Regulation and Stream Standards--In order to evaluate low-flow augmentation for pollution abatement, it is essential that stream standards be used; the effects of flow regulation cannot be measured in effluent sewer lines. For this reason, when evaluating the potential benefits that would result from the inclusion of low-flow regulation as one of the functions of a proposed multiple-purpose reservoir project, those responsible for this evaluation must consider the quality of water in the river downstream of the project. In States where stream standards are in use,

the evaluation can be based on these criteria. In other States, not using stream standards, it becomes necessary to adopt stream water-quality criteria for use in the appraisal of low-flow augmentation.

The choice of a design flow can affect significantly the benefits-cost ratio of a given project and therefore may influence the economic justification of the project. Therefore, the lack of a uniform criteria for establishing design flows among the various States makes it difficult to compare the relative merits of projects in different States. One State may obtain an advantage, in promoting the expenditure of Federal funds for multiple-purpose projects within its boundaries, simply by naming a relatively low design stream flow for purposes of evaluating benefits. For this reason, the design flow is no less important in the economic evaluation of low-flow augmentation than the interest rates. It is noteworthy that the Bureau of the Budget prescribes the interest rate for uniform application by all Federal agencies in the economic evaluation of multiple-purpose water resource developments (Circular A-47, 1952), but there has been no directive to standardize criteria for determining the design flow for purposes of economic evaluation. Because of the lack of any guiding policy on design flow, evaluations of low-flow augmentation in the past have been based on various design stream-flow criteria according to the judgment of the agency responsible for the evaluation.

It should be pointed out that under the existing Federal policy, requiring reimbursement of the cost of low-flow augmentation, any higher apparent benefits resulting from an arbitrarily low design flow would tend to justify greater reimbursement by the beneficiaries of the increased flows. Moreover, a low design flow for the unregulated stream would tend to justify an equally low "no-damage" or compensation flow on a stream regulated for purposes other than pollution abatement.

Water Rights--The use of a waste-treatment design flow of a river before regulation as a base for economic evaluation of pollution-abatement damages or benefits does not necessarily imply any legal right to receive or obligation to provide that design flow on the regulated river. This brings up another legal aspect of flow regulation affecting pollution abatement, one involving water rights and the allocation of water for various purposes among competing water users. Material pertinent to this question is being assembled and studied by the staff of the Low-Flow Augmentation Project. With the view that history can guide the future, the Project is planning a report reviewing the past practices in the matter of compensation flows which have been required in regulated streams by laws and court decisions.

An example of low-flow augmentation by court decree is afforded by the Delaware River Diversion Case in which the Supreme Court, in allowing New York City to divert water for municipal supply from the headwaters of the Delaware River, required that river flows downstream of the storage reservoirs be maintained at certain minimum rates in terms of runoff per square mile of drainage area. The decree also set an upper limit on the required releases in terms of a percentage of the yield of the area from which water is diverted (U. S. Supreme Court, 1931).

An example of flow regulation which reduces the stream flow available for waste assimilation is found in the Patapsco River, a tributary of Chesapeake Bay in Maryland. It has been noted earlier in this report that the 1933 report of the Maryland Water Resources Commission (Wolman et al., 1933) suggested that the proposed diversion of Patapsco River water for municipal use in Baltimore would harm the riparian interests and sewage disposal facilities downstream of the diversion works. This has since been shown to have been an accurate prophesy. In 1953, Baltimore began diverting water from its new Liberty Reservoir on the Patapsco River, thereby reducing the flow in the river below the dam. A manufacturing concern located on the river below the dam instituted suit in the Circuit Court of Baltimore County against the City of Baltimore, seeking a guarantee of a minimum flow in the river at the plant location. The court issued a decree requiring that the city maintain a river flow of 13 million gallons per day (20.1 cfs.) at a gaging station near the mill. It is pertinent to compare this guaranteed flow with the discharge of the river before impoundment in Liberty Reservoir. The minimum daily flow recorded at the gage in question before diversion was 32 cfs., with an instantaneous minimum of 6 cfs. Because the period of record for this gage covered only nine years preceding the regulation by Liberty Dam, data for other gages on the Patapsco River were studied. These gages, with older records, allow an approximation of minimum flows at the gage near the mill for periods not included in the latter's record. By adjustment of the records for the older gages on the basis of drainage area, it is estimated that the daily river flow at the court established check point was as low as 15.1 cfs. on one day in 1941, about 5 cfs. less than the flow now required by the court decree. The daily flows in all other dry periods examined were indicated to have been well in excess of the flow of 20.1 cfs. now guaranteed. The guarantee of a minimum flow of 20.1 cfs. can be considered either beneficial or detrimental to the pollution-abatement program, depending upon the stream flow criterion used for purposes of designing waste-treatment facilities.

These cases on the Delaware and Patapsco Rivers illustrate how, in the absence of clear-cut water policy or legislation controlling flow regulation, the courts are called upon to decide the quantity of water to be made available for waste dilution. They also illustrate court modification of the doctrine of riparian rights which has generally been the basis of water rights in the Eastern States. Such court actions can greatly influence, either positively or negatively, the practice of low-flow augmentation for pollution abatement.

It is anticipated that the current studies of the legal aspects of flow regulation for pollution control will provide a valuable background of information for use in considering future allocations of water for this purpose. It is to be hoped that more comprehensive investigations of the subject will be undertaken by competent authorities on law with the view of providing the information needed by the water-policy makers to insure that low-flow augmentation is not overlooked in the allocation of scarce water resources. This, indeed, is an area for continuing study.

ECONOMIC ASPECTS

It has been previously pointed out that the use of water and storage capacity for the purpose of waste dilution will generally have to compete with other potential water uses. Allocation of limited supplies and reservoir capacity should aim at providing maximum all-around benefits to the greatest possible number of people for the smallest possible monetary investment. Such optimum allocation depends in part on the economic evaluation of the various competing types of water use. Comparative evaluation of these uses will allow the selection of the most beneficial combination of functions to be included in multiple-purpose projects.

To be included, a given function should pass at least one and generally two economic criteria. First, it should show economic feasibility; and second, it should be the most beneficial use of scarce resources. The tool generally applied to water-resources developments to see if these criteria are met is the benefits-to-costs ratio. The first criterion is satisfied if the benefits-costs ratio exceeds unity. The second depends on a comparison of the benefits-costs ratios of the several functions competing for the same resources of water, storage capacity, and available investment funds. In general, the higher the benefits-costs ratio assigned to a given function, the greater the justification for that function over others showing lesser economic ratios. The ratio provides a common yardstick for comparing the economic feasibilities of different functions, of different degrees of development of the same function, and of different projects involving multiple functions.

It should not be inferred that the benefits-costs ratio is the only criterion to be used in determining the desirability of including pollution abatement as a function of a multiple-purpose project. This thought was expressed in the revised edition of the report on Proposed Practices for Economic Analysis of River Basin Projects (Inter-Agency Committee on Water Resources, 1958) in which it is stated:

> "Water pollution control is often one of the effects of water resources development projects. While pollution abatement may contribute significant economic returns to society and individuals, under prevailing practices relatively few of the benefits of pollution control are measured directly in monetary terms. Consequently, intangible considerations, such as the elimination of potential health hazards and aesthetic improvements, are frequently of controlling importance in the justification of pollution abatement."

However, the report also stressed the need to translate as many effects as possible into monetary equivalents. Monetary measures cited were the cost of the most economical alternative means of accomplishing comparable effects and the decrease in cost of water treatment. One of the primary aims of the present investigation has been to find new and improved methods of evaluating the monetary benefits provided by low-flow augmentation for pollution abatement.

It is not essential that flow regulation be provided specifically for waste dilution in order to cause pollution-abatement benefits. Such benefits may result automatically and incidentally from flow regulation for other purposes, such as navigation or hydroelectric power production. These incidental benefits may add measurably to the economic value of a given project. For this reason, pollution control benefits should be evaluated even when incidental to other functions. The inclusion of these added benefits in the economic analysis could change a marginal project with a benefits-costs ratio close to 1.0 to a desirable project with a higher ratio.

Flow regulation for other purposes may reduce critical flows and damage the quality of water available for waste disposal in the unregulated stream. Thus, flow regulation can have a detrimental effect on pollution abatement programs; it can cause monetary damages as well as benefits. The evaluation of these damages is no less important than the evaluation of benefits. Such damages can be measured in terms of the cost of additional waste-treatment or other pollution-abatement measures that would be required as a result of reducing critical flows or degrading water quality in the regulated waterway. These costs are properly included in the overall costs of the water resource project for comparison with benefits in the benefits-costs ratio.

The economic analysis of water development projects depends on both policy and technical considerations. The specific method of allocating costs and benefits among several functions of a multiple-purpose project is a matter for policy decision, as is the interest rate and the period of amortization. The actual monetary value of damages or benefits, however, must rely on the degree of added or reduced waste treatment attributed to the project. The determination of the change in waste-treatment requirements resulting from flow regulation is primarily a technical matter, except for the establishment of waste-treatment design criteria. Most of the efforts of the current research project have been directed toward the technical evaluation of these changes in waste-treatment. However, consideration has been given to the need for supplemental studies to supply the information and techniques necessary for the translation of changes in pollution-abatement requirements into monetary values. Some of the areas which will require detailed study include:

1. Costs of treating domestic and industrial wastes by various methods,
2. Cost of water treatment as a function of the quality of the raw water and its variability,
3. Costs of reducing the heat content of cooling-water discharges by various methods,
4. Damages or benefits to fisheries, wildlife, and recreational interests, and
5. Impact of greater growth potential on the economy of an area.

These studies are generally beyond the scope of the present research project, although considerable material pertinent to these problems has been assembled in the files of the project.

TECHNICAL ASPECTS

Most of the work of the present study has been concentrated on the extremely complex technical aspects of low-flow augmentation for stream-pollution abatement. Current studies are indicating new methods by which stream data may be obtained, interpreted, and ultimately used to estimate the flows which would be required of a multi-purpose reservoir project to provide various degrees of pollution abatement. However, many areas of doubt and conflict have become apparent. In several cases these areas have been explored in attempts to resolve the conflicts.

This phase of the investigation has been primarily concerned with organic wastes which exert a demand on the oxygen resources of a stream. The use of low-flow augmentation for pollution control, however, is not limited to these wastes. In fact, flow regulation will probably assume its greatest economic significance when other wastes which can be disposed of only by dilution are encountered. Some examples are acid mine drainage, toxic wastes, high mineral contamination, oil-well salt pollution, dye or other coloring wastes, and high-temperature cooling wastes. Although the flows which will be necessary to reduce the pollution level of such wastes may be generally determined by relatively simple dilution requirements, the possible effects of flow regulation on waste problems of this type are now under consideration. A notable example of the control of "heat" pollution is in the Beaver River Basin of Ohio and Pennsylvania where regulated flows are provided to control the effects of cooling-water wastes from the steel mills and other large industrial concerns. It is understood that flow regulation is currently being considered as a means of reducing the effects of highly mineralized waters originating in the upper portions of the Red River Basin in Oklahoma.

Methods have been developed for transposing the design flow of an unregulated stream to an equivalent "no-damage" flow in the same stream after impoundment and regulation, taking into account any changes in water quality attributed to impoundage. This "no-damage" flow in the regulated stream becomes the basis for comparison with the regulated flows actually provided to show quantitatively the extent of benefits or damages to a pollution-abatement program. These methods will be described in a separate report not yet prepared.

Oxygen Balance Formulas--The concern with the relationship between a stream's flow rate and its ability to assimilate organic wastes has directed the project's attention and main efforts toward the complex problem of the dissolved-oxygen balance in surface waters. The biochemical oxygen demand (BOD) of organic wastes is one of the principal factors necessary for the analysis of the oxygen balance. A bibliography (Hull, 1959) on BOD has been prepared as an aid in investigating some of the relationships

between standard bottle BOD's and the *in situ* respiration in the stream. This bibliography, though not intended for publication, will be reproduced in a limited number of copies for distribution to interested workers in the field.

The oxygen balance of flowing streams was formulated more than 30 years ago by Streeter and Phelps (1925). The original formula, in its differential form, is

$$\frac{dD}{dt} = K_1 L - K_2 D \qquad (1)$$

and in the integrated form becomes

$$D = \frac{k_1 L_a}{k_2 - k_1} (10^{-k_1 t} - 10^{-k_2 t}) + D_a 10^{-k_2 t} \qquad (2)$$

in which D_a = initial D.O. saturation deficit of water, mg./l.
D = saturation deficit after time t, mg./l.
L_a = initial ultimate first-stage BOD, mg./l.
K_1 = 2.3 k_1 = coefficient defining the rate of deoxygenation, per day
K_2 = 2.3 k_2 = coefficient defining the rate of atmospheric reaeration, per day
t = elapsed time, in days.

The Streeter-Phelps formula is now known to lack some of the factors controlling the overall dissolved-oxygen balance in most surface waters. However, if used with knowledge of its limitations, and if the coefficients are determined empirically from stream data, the formula can be used to predict the so-called oxygen sag with reasonable accuracy. In spite of its deficiencies, the formula is widely used by pollution-control agencies in determining pollution-abatement requirements. It has been used extensively by the Public Health Service in its studies of stream-sanitation requirements, including investigations of low-flow augmentation. The Streeter-Phelps formula is generally considered to be the "standard" method for predicting the dissolved-oxygen conditions in unimpounded sections of surface streams.

Fair (1939) published an analysis of the Streeter-Phelps oxygen-sag equation in which he presented simplified formulas which can be used to predict the critical, or maximum deficit, D_c, at the so-called critical sag point, the point of major interest in the study of a stream's waste-assimilative capacity. These simplified formulas are

$$k_1 t_c = \frac{1}{f-1} \log \left\{ f \left[1-(f-1) \frac{D_a}{L_a} \right] \right\} \qquad (3)$$

and

$$D_c = \frac{L_a}{f} 10^{-k_1 t_c} \qquad (4)$$

in which $f = k_2/k_1$, the "self-purification" coefficient,
c = subscript denoting the values at the critical sag point,

and other factors are as previously defined.

The simplified formulas of Fair do not sacrifice any accuracy; they give exactly the same results as the more cumbersome form of equation 2 for the special point of interest, the critical sag point. They are merely mathematical modifications of the Streeter-Phelps formula. For purposes of low-flow augmentation analysis, it is often convenient to use the Fair modifications.

Another modification of the Streeter-Phelps sag formula was presented by Thomas (1948). The Thomas formula is

$$D = \frac{k_1 L_a}{k_2 - k_1 - k_3}\left[10^{-(k_1+k_3)t} - 10^{-k_2 t}\right] + D_a 10^{-k_2 t} \qquad (5)$$

in which k_3 is the "constant" or coefficient of proportionality defining the rate of removal of BOD from the flowing water due to deposition. In turbulent sections of a stream during relatively high flows, organic materials previously deposited during quiescent periods may be scoured, resulting in a negative value for k_3. If there is neither deposition nor scouring of solid organic material, k_3 is equal to zero, and equation 5 becomes identical with equation 2.

The Thomas modification (equation 5) represents an attempt to adjust the oxygen-sag formula for one of the factors, mentioned earlier, now known to be generally significant but not accounted for in the original Streeter-Phelps equation. However, other factors, also omitted, are probably equally important, such as photosynthetic reoxygenation, benthal oxygen demand, volatilization and loss to the atmosphere of BOD, longitudinal mixing, and other obscure effects. Because neither the original sag formula nor the Thomas modification accounts for these various factors and their complex inter-relationships, there is little to choose between them. However, either of them, if used empirically to determine the coefficients from observed stream data, can be used as an empirical formula to predict with reasonable accuracy the true oxygen sag. The chief requirement is that the conditions for which predictions are made should not range very far from those prevailing when making the observations to determine the coefficients, k_1, k_2, and in the case of the Thomas modification, k_3.

In the Fair modification, the self-purification coefficient, f, provides a convenient means of including all the obscure factors controlling the oxygen balance in a stream. In practice, the terms in the formulas other than the self-purification coefficient can be determined from field and laboratory tests and inserted in the Fair formulas, providing a solution for f. The coefficient determined in this manner includes the effects of whatever phenomena influence the deoxygenation and reoxygenation rates in the stream.

During the course of the present investigation, several simplifying modifications of the oxygen-sag formula have been developed, along with

techniques for specific application to the problem of low-flow augmentation for pollution abatement. Only brief summaries of these simplifications can be included here; more detailed explanations will be presented in separate reports.

Hull (in press) has derived a simple formula for the determination of the self-purification coefficient, f. The relationship is

$$f_c = \frac{L_c}{D_c} \qquad (6)$$

in which L_c is the ultimate first-stage BOD remaining at the critical sag point and D_c is the oxygen deficit, also at the critical sag point. A technique for using this simplified formula has been developed for use in stream surveys. The value of the formula and technique is in its simplicity. Once the critical sag point is located, it requires only three measurements: temperature, dissolved oxygen, and BOD. The need to determine k_1, k_2, or time-of-flow is eliminated. The formula applies only to the critical sag point, however, and therefore the coefficient obtained by this method cannot be generally used throughout the entire deoxygenation zone of a stream. In spite of this limitation, the simplified formula is expected to become a useful tool in studies of low-flow augmentation and in stream-sanitation surveys generally. Several uses for the relation have been suggested, including the study of the effects of temperature and flow rate on the self-purification characteristics of a stream. Both of these are significant in the analysis of flow regulation for pollution abatement.

LeBosquet and Tsivoglou (1950) have presented a simplified oxygen-sag formula and technique which allows analysis of the relationship between the critical oxygen deficit and the flow rate without the need of BOD or time-of-flow measurements. This has proved to be useful in general stream work where the initial dissolved-oxygen concentration at the point of waste introduction is near the equilibrium or saturation concentration. However, the technique has limited usefulness in flow-regulation studies; one of the common effects of impoundments is marked depletion of dissolved oxygen concentration in the water discharged to the stream below the reservoir.

Another feature of the LeBosquet-Tsivoglou short-cut procedure is its underlying assumption of a constant BOD load from the waste source. This assumption limits the usefulness of the method in many situations where varying loads are discharged into the stream.

Hull (in preparation) has derived a formula which is intermediate in complexity between the Fair modification and the LeBosquet-Tsivoglou formula. This formula overcomes the limitations of the LeBosquet-Tsivoglou technique; it can be used with any initial dissolved oxygen deficit and BOD load. The new formula is derived by combining the Fair modifications (equations 3 and 4) and solving them simultaneously to obtain the following formula for the critical deficit:

$$D_c = \frac{L_a}{f}\left[f - f(f-1)\frac{D_a}{L_a}\right]^{\frac{1}{1-f}} \qquad (7)$$

Equation 7 involves only four factors: D_a, D_c, L_a, and f. The deoxygenation coefficient, k_1, and the time-of-flow, t_c, have been eliminated, which greatly simplifies the work required in field and office studies of the oxygen sag.

Equation 7 is merely a mathematical simplification of the basic Streeter-Phelps formula (equation 2) for the dissolved oxygen deficit, providing an easy solution for the specific point of special interest, the critical sag point, or point of maximum deficit. From a theoretical standpoint, therefore, the simplified formula is no better than the basic equation from which it is derived. However, because of the elimination of two factors which are relatively difficult to determine accurately, the simplified formula tends to increase the overall accuracy of oxygen-sag analysis, in addition to the savings in time and work it allows.

Experience to date has shown equation 7 to be a useful means of sag analysis for purposes of low-flow regulation. Carbaugh (in preparation) has developed several analytical techniques which allow rapid solution of the simplified formula. The formula and rapid techniques allow simple and fast computations of flow requirements for a wide range of potential controlling conditions. Thus the flow requirements can be determined for any quality of water in the regulated stream and for any given waste load. Conversely, the waste-assimilative capacity of a stream to be regulated can be predicted, using predicted values of water quality and given scheduled flow releases. Where variations in quality of the receiving water, or errors in the predicted quality, are anticipated, the simplified formula and techniques afford a convenient method of studying the significance of these variations or potential errors in predictions. For example, as discussed later in this report, the temperature dependency of the self-purification characteristics of surface streams is an area in which the available information is confusing and conflicting, leaving room for error in transposing summer stream observations to winter flow requirements for pollution abatement. The significance of any reasonable error in the estimated value of the self-purification coefficient, f, in determining the required regulated flow (and therefore the economic feasibility of the low-flow project) can be studied easily with the simplified methods.

Other uses of the simplified formulas and procedures are proposed and explained in detailed reports to be issued separately.

Temperature Effects--Most stream-sanitation studies in the United States in the past have been concerned with the critical period of low flows and high temperatures normally occurring in late summer or early

fall. Higher flows and colder temperatures during other times of the year have combined to give relatively high self-purification capacity in natural, unregulated streams. However, with a regulated stream, storage of flows during the wet seasons may reduce the flows to such an extent that the stream, in spite of lower temperatures, cannot assimilate as great a waste load as it can absorb safely in the warm season with relatively high flows. Information is needed to allow extrapolation of summer self-purification factors to other seasons. Temperature-correction coefficients have been established by various investigators in laboratory studies and have been used extensively for adjustment of stream data over limited ranges of temperature. However, recent studies have indicated serious doubt as to the validity of these thermal coefficients for the annual range of temperatures normally experienced in surface waters. In addition, it appears highly improbable that temperature will be the only seasonal variable significantly affecting the assimilation of wastes. Factors other than temperature, such as sunlight, are undoubtedly important in the oxygen balance of streams and impoundments. These seasonal factors deserve more consideration than they have received in the past, even in studies of natural streams. In impoundments and in regulated rivers, they may be all important.

Because of the need for reliable methods for transposing stream self-purification characteristics from one season to another, involving a wide range of temperatures, a study was undertaken in order to evaluate existing information and past practices relating to the effects of temperature on the waste-assimilative capacity of surface waters. Two memorandum reports (Hull and Carbaugh, 1958, and Carbaugh, 1959) were prepared primarily for use as guides in the current studies of low-flow augmentation and have not been released for publication. However, as the findings would have general applicability to stream-sanitation studies, it is planned to put these memoranda into a form suitable for publication at an early date. The reviews covered the temperature dependency of the biochemical oxygen demand reaction and of the atmospheric reoxygenation rate. Highlights of the review are given in the following summaries.

Temperature versus k_1.--The temperature dependency of the deoxygenation coefficient, k_1, was found by Streeter and Phelps (1925) to be defined by the empirical formula

$$\frac{k_1'}{k_1} = \theta_1^{(T'-T)} \qquad (8)$$

in which θ_1 is the thermal correction coefficient. From a limited amount of data obtained from three different laboratories in Cincinnati, Boston, and Washington, Streeter and Phelps estimated the value of θ_1 to be 1.047.

Theriault (1927), working independently, derived the same relationship as that of Streeter and Phelps. He obtained a value of 1.053 for θ_1 in the temperature range from 9° C. to 20° C., and another value of 1.049 for the range from 20° C. to 30° C. He stated that:

"With due regard for limitations of experimental and statistical procedures, it must be concluded that in the interval from 2° to 30° C., the deoxygenation constants may be defined accurately in terms of equation...[8]deduced by Streeter and Phelps."

The value of 1.047 for the thermal correction coefficient of k_1 has been widely accepted. Fair (1939) used 1.047 in developing the temperature effects of his self-purification coefficient, f. Phelps (1944) stated that the value of 1.047 appears to apply with fair approximation to a temperature range of 9° C. to 30° C. This value is still commonly used today, more than 30 years since its determination by Streeter and Phelps, by workers in the stream-sanitation field.

In view of the general acceptance of the value of 1.047 for θ_1, there might appear to be little reason for questioning its validity. However, other values have been reported in the literature since the original determination by Streeter and Phelps. Therefore, it appears worthwhile to examine and compare the reported values to see if explanations can be found for the inconsistencies.

Moore (1941) investigated the temperature relation of k_1 in the range between 0.5° C. and 20° C. He reported two values of the thermal correction coefficient: 1.145 between 0.5° C. and 5° C.; and 1.065 between 5° C. and 20° C.

Gotaas (1948) appears to have performed the most extensive experimentation to date on the temperature effect on deoxygenation. His experiments covered the temperature range from 5° C. to 40° C., in 5-degree increments. He summarized his findings in the form of three different values for θ_1, each corresponding to a given temperature range, as follows:

Temperature, °C.	θ_1
5 - 15	1.108
15 - 30	1.041
30 - 40	0.9657

One consistent characteristic within each set of data reported is the decreasing value of θ_1 with increasing temperature. To test this characteristic further, the data reported by the various authors have been compiled in table 1. Direct comparison is difficult because of the differences in the temperature ranges reported. In order to eliminate this difficulty, the midpoint of each temperature range has been determined and listed in the table. The reported thermal coefficients were then plotted against the midpoint of the experimental temperature range. The resulting plot is shown in figure 1. The horizontal line through each plotted point shows the range of temperature covered by the experiments from which the value of θ was determined.

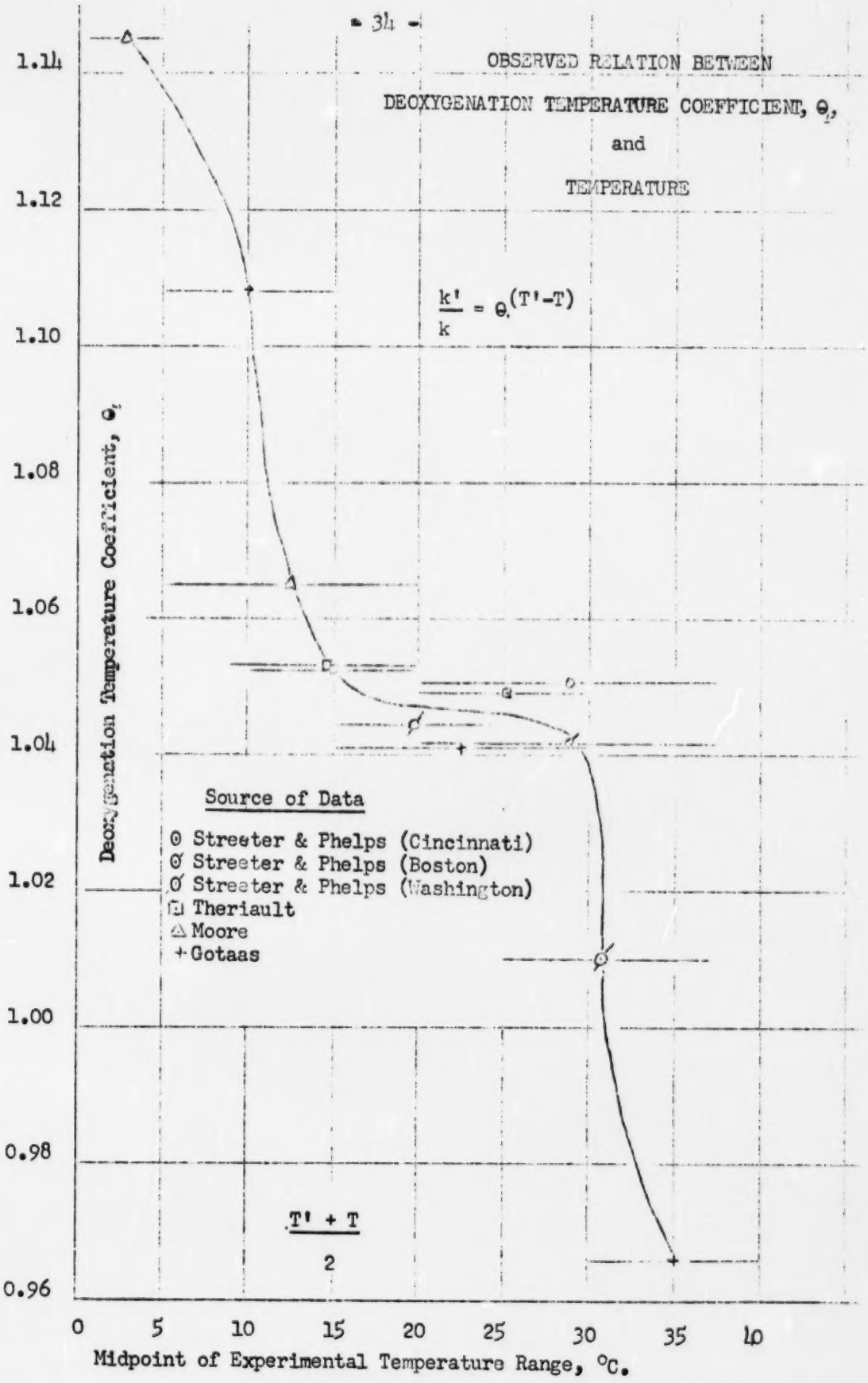
The data presented in table 1 and in figure 1, taken together, show a remarkably consistent trend, all the more so in view of the fact that

TABLE 1

Summary of θ_1 Values Reported by Various Investigators

Author(s) or Investigator (s)	Date Reported	θ_1	Temperature, °C. Range	Midpoint
Streeter & Phelps	1925	1.0524	10 - 20	15
"	1925	1.0441	15 - 24.5	19.75
"	1925	1.0504	20 - 37.5	28.75
"	1925	1.0415	20 - 37.5	28.75
"	1925	1.01*	24.5-37	30.75
Theriault	1927	1.053	9 - 20	14.5
"	1927	1.049	20 - 30	25
Moore	1941	1.145	0.5-5	2.75
"	1941	1.065	5 - 20	12.5
Gotaas	1948	1.108	5 - 15	10
"	1948	1.041	15 - 30	22.5
"	1948	0.9657	30 - 40	35

* Streeter and Phelps discarded this value because it was "...obviously out of harmony with the others."


OBSERVED RELATION BETWEEN
DEOXYGENATION TEMPERATURE COEFFICIENT, θ1,
and
TEMPERATURE
k'/k = θ1^(T'-T)
Deoxygenation Temperature Coefficient, θ1
1.14
1.12
1.10
1.08
1.06
1.04
1.02
1.00
0.98
0.96
Source of Data
Streeter & Phelps (Cincinnati)
Streeter & Phelps (Boston)
Streeter & Phelps (Washington)
Theriault
Moore
Gotaas
(T' + T)/2
0
5
10
15
20
25
30
35
40
Midpoint of Experimental Temperature Range, °C.

they represent the work of six different investigators or groups using different techniques over a period of more than 20 years. On the basis of these data, it seems clear that there is no support for the hypothesis that θ_1, the thermal coefficient of k_1, as defined by equation 8, is a constant. It appears more likely that θ_1 is itself a function of temperature. It also appears that the relationship is approximated by an ogee curve similar to that shown in figure 1.

It is interesting to note that in the original deduction of the value of 1.047 for the thermal coefficient, Streeter and Phelps did not use the value of 1.01; they eliminated it as being "obviously out of harmony with the others." Actually, it appears anomolous only if the hypothesis of a constant thermal coefficient throughout the temperature range is assumed. On the basis of an ogee relationship, the value, 1.01, appears to be rather consistent with the other data.

The most significant conclusion suggested by the foregoing summarized review is that the formulation presented first by Streeter and Phelps, equation 8, and derived separately by Theriault (1927) is not adequately supported by experimental data. The available data, examined in toto, appears to disprove the hypothesis of a geometric relationship between temperature and k_1, with a constant value of θ in the formula. In a separate report now under preparation, an attempt is made to derive a relationship which adequately describes the temperature dependency of k_1 for the purposes of low-flow augmentation studies.

It seems evident that further investigation is needed on the relationship between temperature and the deoxygenation rate. Until this is done, the application of BOD data obtained at one temperature to another temperature will be of doubtful value. This is especially true for the wide range of temperatures involved in low-flow augmentation studies.

Temperature versus k_2--Among the many studies of the effects of temperature on the atmospheric reoxygenation rate, there is a conspicuous lack of agreement in the resulting thermal correction coefficients reported. This discord has created doubt as to the proper coefficient to apply in low-flow augmentation studies. It has been found that computed flow requirements vary significantly when based on different thermal coefficients within the range of the reported values. The special importance of temperature-correction factors for purposes of flow regulation for pollution abatement led to a critical review of the literature. A report of that review is now under preparation. The review was aimed specifically at revealing the effects of temperature on the atmospheric reoxygenation-rate coefficient, k_2.

The effects of temperature on the rate coefficient are indicated to be the result of changes in density, viscosity, surface adsorption, and molecular diffusivity. The relationship desired, however, is indicated to be an empirical one based on the gross effects of temperature on these various factors.

The methods of expressing the temperature effects on the atmospheric reoxygenation-rate coefficient are given by

$$k_{2(T)} = k_{2(20)}\left[1.0 + S\ (T-20)\right] \qquad (9)$$

and

$$k_{2(T)} = k_{2(20)}\ \theta^{(T-20)} \qquad (10)$$

where temperature (T) is measured in the Centigrade scale. Both equations express the relationship by indicating a change in the value of k_2 with respect to the value of k_2 at 20° C. The temperature-correction coefficient, S, used in equation 9 times 100 is the per cent change in k_2 per degree Centigrade from the value of k_2 at 20° C. In a similar manner, the correction coefficient, θ, of equation 10 minus 1.00 times 100 is the per cent change in k_2 compounded per degree Centigrade from the value of k_2 at 20° C. It will be noted that the first equation indicates an arithmetic increase while equation 10 indicates a geometric increase.

A total of 49 references were critically reviewed. An additional 36 references were investigated, but they did not contribute quantitative information. Of the references specifically reviewed, only 15 are not based on the work of previous investigators. Of these 15 "original" studies, only four can be considered applicable to the conditions of a natural flowing stream. In reviewing these studies, it was observed that temperature-k_2 relationships which are unsupported by experimental observations are not reliable. It was also assumed that relationships based on experiments with bubble aeration, disk aeration, aeration at weirs, or from observations of an unmixed system do not represent flowing surface waterways. The experimental procedures reported by Streeter et al. (1936), Downing and Truesdale (1955), Gameson et al. (1956), and Truesdale and Vandyke (1958) appear to have represented adequately the conditions of a natural stream.

The studies reported by Downing and Truesdale (1955) were performed in a mixed vessel and the other three "natural" investigations were conducted in channels. The study by Gameson et al. (1956) did not adequately investigate temperature effects on the reoxygenation rate. Although many difficulties are encountered when the channel system is used, they do not, in themselves, detract from the significance of the experimental results. However, in view of various techniques used by Streeter et al. (1936) it is felt that the correction coefficient for the atmospheric reoxygenation-rate coefficient (k_2) determined by them is not too reliable. The results of the investigations reported by Downing and Truesdale (1955) seem more significant than those of Truesdale and Vandyke (1958) in that the difficulties of the channel system were not experienced.

Based on the critical review summarized above, it appears that the temperature-correction relationship for the specific rate coefficient of atmospheric reoxygenation (k_2) is best approximated by :

$$k_{2(T)} = k_{2(20)}\left[1.0 + 0.02\ (T-20)\right] \qquad (11)$$

This relationship indicates a two per cent change in k_2 per degree Centigrade from the value of k_2 at 20° C.

It must be noted here that the above conclusion is based primarily on the reported results of Downing and Truesdale (1955). Additional evidence is needed. As stressed in the review now being prepared, the experimental techniques employed must simulate a natural flowing stream to yield a valid relationship.

With regard to the existing conflict involving the values of θ used in the geometric relationship between temperature and k_2, ranging from 1.0159 to 1.047, it should be noted that for a limited range of temperature, the geometric relationship using the value of 1.0159 (or 1.016) for θ yields results not substantially different from those obtained with the linear relationship, equation 11. This supports the lower range of θ values for the geometric formula. This and other evidence lead to the conclusion that the higher value of 1.047 for θ is unjustified. On the other hand, available evidence does not appear adequate to support the degree of accuracy implied by the use of three or four decimal places in the lower values of θ reported. For purposes of the current low-flow augmentation studies, it has been concluded that the value ofθ should be rounded to 1.02. This conclusion should not be interpreted to mean that 1.02 is the correct value for θ or that there is no need for refinement or further study of this coefficient. It means only that refinement cannot be justified on the basis of available evidence.

With regard to the other conflict between a linear relationship between temperature and k_2 on the one hand, and a geometric relationship on the other, it is felt that for relatively small temperature corrections there is little to choose between the two without further experimental evidence. The two methods do not yield significantly different results unless a large temperature correction is involved. For large temperature changes, it appears that the available evidence favors the use of the linear relationship.

It should not be assumed generally that any temperature-k_2 relationship will apply to the total reoxygenation in a stream. Photosynthesis is now generally recognized as contributing significant portions of the dissolved oxygen found in most surface waters. There is no reason to believe that the temperature dependency of photosynthetic oxygenation is the same as that of atmospheric reaeration.

Temperature versus f--In the same work in which the self-purification coefficient, f, was first introduced, Fair (1939) discussed the temperature dependency of f and presented the relation

$$f_T = f_{20} \times 0.970^{(T-20)} \qquad (12)$$

which was based on the geometric formulas for the effects of temperature on k_1 (equation 8) and on k_2 (equation 10), with thermal coefficients of

1.047 and 1.0159, respectively. In using the value of 1.0159 as the thermal coefficient of k_2, which was originally presented by Streeter (1926), Fair made no comment on the correction of that value reported by Streeter, Wright, and Kehr (1936) three years before the publication of Fair's work (1939).

In a widely used book on stream sanitation, Phelps (1944) reviewed the temperature effects on stream purification. He cited the values of the thermal coefficients for k_1 and k_2 reported by Streeter and Phelps (1925) and by Streeter, Wright, and Kehr (1936), which indicated that both temperature coefficients were sensibly the same and approximately equal to 1.047. Using the same value for both would result in f being independent of temperature; that is , the constant given as 0.970 in equation 12 would be equal to 1.0. However, later in his book, Phelps stated:

> "The temperature coefficient of f is the ratio of the temperature coefficients of its two factors which we have seen to be 1.015 (taking Streeter's surface aeration coefficient, r_o) and 1.047. This ratio is 0.97..."

It is not clear why Phelps chose to use 1.015, which he accepted as the thermal correction coefficient for the surface aeration coefficient, r_o, inasmuch as he indicated that f is the ratio, k_2/k_1, not r_o/k_1. However, in using 1.015, he obtained approximately the same thermal coefficient for f that Fair had obtained; their two values agree to the second decimal place.

LeBosquet and Tsivoglou (1950) apparently disagreed with Fair (1939) and Phelps (1944), stating that

> "The temperature correction coefficient (1.047) for k_2 in the formula... [equation 10] is substantially the same as that for k_1 and, therefore, the ratio k_2/k_1 may be expected to remain constant with variable temperature, under any given set of conditions. This conclusion, that the two temperature correction coefficients are the same, has been borne out by studies of atmospheric reaeration by Streeter, Wright, and Kehr... [1936]. The conclusion is also presented by Phelps... [1944]." (Emphasis added.)

The underlined sentence in this quotation evidently refers to Phelps' apparent acceptance of the value of 1.047 as the thermal correction coefficient for k_2 as well as for k_1. However, as already pointed out, Phelps used the ratio of 1.015 and 1.047 to obtain the value of 0.97 for the temperature coefficient of f. Phelps actually concluded that

> "...there is a decrease in the value of f of about 3 per cent, compounded, for each rise of 1° in temperature."

It should be remembered that Fair (1939), Phelps (1944), and LeBosquet and Tsivoglou (1950) all based their conclusions regarding the effects of temperature on f (or k_2/k_1) on the same value of the thermal coefficient of k_1, 1.047, as presented by Streeter and Phelps (1925).

However, as shown earlier in this report, there is far less than unanimity concerning the true relationship between k_1 and temperature, as shown by the works of Moore (1941), Gotaas (1948), and the present writers (see figure 1).

The reviews of the effects of temperature on the self-purification characteristics of surface streams, summarized herein, have led to an inescapable conclusion that our knowledge of these temperature effects is inadequate for the needs of flow-augmentation evaluation. This conclusion is supported more fully in the complete reviews, to be presented in other reports, than can be done in this summary.

It is anticipated that the doubtful and conflicting areas regarding temperature effects will be resolved by further research. It is believed that the simplified formulas presented earlier in this report provide convenient tools for study of the temperature dependency of the self-purification coefficient, f. Accurate determination of the temperature-f relationship would afford a good foundation for studying the temperature effects on k_1 and k_2, the components of f.

Temperature vs. Oxygen Solubility--There is, at present, an unresolved question regarding the solubility of oxygen in water at various temperatures. Since the solubility of oxygen is basic to the determination of the oxygen balance in streams, this matter has been followed closely. Differences of as much as 4 per cent are noted between the "Standard Methods" (A. P. H. A., 1955) values and the oxygen solubilities reported by Truesdale et al. (1955). At present, the interest of the Low-Flow Project is limited to recognition of the differences. Research to resolve the question is now being conducted in another project at The Johns Hopkins University. Resolution of the conflict is badly needed to improve the reliability of the computations involved in low-flow augmentation studies, as well as for many other purposes in stream-pollution control.

Alternative Methods of Pollution Abatement

Problems of alternate methods of pollution abatement involve both economic and technical aspects. The monetary benefit assigned to flow augmentation for pollution abatement cannot be greater that the cheapest alternative method to provide the required degree of pollution control. This was expressed by the Presidential Advisory Committee on Water Resources Policy (McKay et al., 1956) as follows:

> "No purpose or separate segment of the project should be developed beyond the point where the benefits added for the last increment are equal to the cost of its inclusion. Each segment of the project should be more economical than any alternative means, public or private, available in the locality for accomplishing the given purpose that would be expected to develop in the absence of the project." (Emphasis added.)

The same idea was set forth in the earlier report on economic evaluation by the Federal Inter-Agency River Basin Committee (F. I. A. R. B. C., 1950), in which the Corps of Engineers and the Department of the Interior

indicated that benefits to pollution abatement were measured by the cost of providing the most economical alternative methods of waste treatment or disposal.

Most evaluations of pollution abatement benefits from flow regulation which have been carried out in the past have been based on the potential reduction of waste treatment, without reference to other possible means of disposal. More specifically, the reduction has frequently been considered as the elimination of secondary or biological treatment of municipal wastes or of an equivalent advanced stage of treatment of industrial wastes.

Recent developments have created the need for consideration of "alternative" methods of waste disposal which are inherently more economical than conventional secondary treatment. The growing use of oxidation ponds for municipal wastes and of holding lagoons for industrial wastes portends more economical waste disposal.

Originally thought suitable only for sunny, arid lands such as the Southwest, sewage-oxidation ponds are now found in many northern States and even in Canada. The Department of Public Health in the Province of Saskatchewan reports (Schaeffer, 1958) that in recent years almost all new waste-disposal installations consist of sewage lagoons, and that in a number of instances a trickling filter plant or even an activated sludge plant has been abandoned in favor of a sewage-oxidation pond. The Pollution Control Commission of the State of Washington reports (Neale, 1958) that in several instances of conflict involving waste disposal and low stream flows, it has been the practice of the Commission to request complete land disposal either as irrigation waters or by the use of non-overflow impoundments. Sewage lagooning has not been used expensively in the East, but recently the Pennsylvania Sanitary Water Board issued the first permit for a sewage-stabilization pond in Allegheny County, near Pittsburgh (Anon., 1958).

Waste-holding lagoons for industrial wastes, with controlled discharge coordinated with rate of flow in the receiving stream, are now used in several locations throughout the United States. It is reported that waste-holding lagoons are used to store beet-sugar wastes at a plant in Minnesota (Rogers and Smith, 1953). The wastes are stored for a period of about 80 days during the winter. After the ice breakup in early spring, the lagoons are emptied at a rate controlled to maintain a predetermined oxygen concentration in the river.

Krancher (1951) reported that a strawboard mill in Indiana uses waste lagoons for waste reduction as well as for proportioning the waste discharge to the White River. The Indiana Stream Pollution Board required that waste discharges from the plant not exceed the dilution ratio of 1 to 350. The waste discharge is regulated by means of a Telemark system to determine the river stage. This case illustrates a significant point with respect to low-flow augmentation for waste dilution. Flow augmentation would be economically feasible in this case only if it would be cheaper to store 350 gallons of river water for an extended period to dilute each gallon of waste discharged. Here is a situation where it is probably cheaper to store one gallon of waste until the natural river

flow is adequate for dilution, than to store 350 gallons of river water until needed for dilution purposes.

Other waste-holding lagoons are in use at a Kraft pulp and paper mill in Alabama (VanDerveer, 1959), at a sulfite pulp mill in Maine (Lambe and Anderson, 1955), and at an unbleached sulfate pulping mill in Virginia (Crawford, 1947). These and other successful applications of holding lagoons, with discharge controlled to comply with dilution requirements in the stream, make it obvious that this method has to be considered along with more conventional waste-treatment systems, in the economic evaluation of low-flow augmentation.

A closely related aspect concerns the dilution water made available at frequent intervals in streams below hydroelectric power dams operated for peaking power production. Such flow regulation for power production would in many cases make low-flow augmentation specifically for pollution abatement economically infeasible. The availability of the frequent peaking flows for dilution of wastes automatically makes lagooning attractive, and in many situations, cheaper than conventional waste treatment. In such a situation, the "most economical alternative method" of waste disposal would be the use of short-term holding lagoons with detention periods measured in hours or days. To accomplish the same degree of pollution abatement by low-flow augmentation would require long term storage of dilution water with detention periods measured in months. To show feasibility for flow augmentation, it would be necessary to show that hundreds of gallons of clean water could be stored for months at a cost less than that of storing one gallon of wastes for a few days.

These incidental benefits from hydroelectric power production would be reduced or eliminated where flows during off-peak power flows were drastically reduced below the level of the natural low flows for the unregulated river. The benefits would also depend on the quality of the water discharged for power purposes, as that quality controls the waste-assimilative capacity of the stream below the power project.

The relationship between water quality of peaking-power discharges, frequency of discharge, and the sizing of waste lagoons is one of the technical aspects being studied by the Low-Flow Augmentation Project as a necessary prerequisite for the economic evaluation of any multiple-purpose water development project which includes hydroelectric power as a function. Because both sewage-oxidation ponds and waste-holding lagoons are potentially more economical than conventional methods of waste disposal, they must be considered in the economic evaluation of low-flow augmentation. It can be safely predicted that it will not be practical or possible to use these cheaper methods in all situations. Where this is so, the numerator of the benefits-costs ratio will be derived from the value of the more conventional treatment methods which can be replaced by flow augmentation.

Effects of Impoundments on Water Quality

Impoundments created for any purpose may affect the quality of water in the stream and consequently its waste-assimilative capacity. The primary water-quality characteristics that are generally influenced by impoundments and which in turn control the waste capacity of the stream are temperature, dissolved oxygen, and BOD. These three factors may influence the assimilative capacity within the impounded section itself as well as in the natural stream section draining the impoundment. Additional factors influencing waste capacity in the impounded section of the stream may be significantly different after impoundment than before. These factors must all be taken into account in the analysis of a proposed reservoir development as related to pollution abatement.

A card index of literature covering the effects of impoundments on water quality was assembled in the files of the Low-Flow Project as an aid in studies of flow requirements for pollution abatement. At the request of the Robert A. Taft Sanitary Engineering Center of the Public Health Service, a bibliography (Hull, 1959) on this subject was prepared from the card index for limited distribution.

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Although the effects of impoundments on water quality are generally known, there is little information available in the published literature on methods that can be used in predicting these effects quantitatively. The oxygen-sag relationship developed by Streeter and Phelps (1925) for flowing streams does not apply to deep impoundments. Some of the factors contributing to the oxygen balance which are not included in the Streeter-Phelps formula (except in empirically determined coefficients) are indicated to be highly significant in impoundments. Photosynthetic oxygenation is one of these factors. Data are being assembled for use in studying these factors with the aim of developing methods to predict their effects on water quality and waste-assimilative capacity.

Miscellaneous

Several side problems have presented themselves in the course of the present investigation which have required study to evaluate their potential effects on low-flow augmentation. One such problem involves the interpretation of BOD data obtained in the laboratory, when different dilutions of the same sample result in different computed BOD's, with the higher dilutions giving higher BOD's. This is generally interpreted to mean that there is an inhibitory effect in the more concentrated samples as a result of toxic materials; the higher dilutions tend to eliminate the toxicity and allow the BOD reaction to take place at a more normal rate. This effect could be quite significant in a stream in which flow requirements are computed on the basis of dilution of oxygen demanding wastes. The dilution of toxicity would tend to nullify the dilution of BOD. Because of this phenomenon, it is important to know whether toxicity is present in a stream for which flow augmentation is proposed for dilution of organic wastes.

In studying the toxicity effect in relation to flow augmentation, the Project encountered a complication in the form of a synergistic effect noted in the BOD of mixtures of polluted river water and unpolluted river water collected upstream of the waste source. The BOD of the mixture was frequently greater than could be computed from the BOD's of unmixed samples of polluted and unpolluted water. This could be an indication of toxicity. However, a similar result was attributed by Theriault and Hommon (1918) to a greater oxygen demand of the dilution water when incubated with waste or sewage than when incubated alone. In explanation, they suggested that the small numbers of attenuated bacteria in the unmixed dilution water were not capable of attacking the organic matter present at a normal rate; but in the mixture, the organic matter of the dilution water is subjected to the action of a greater variety of less attenuated bacteria. They pointed out that dilution water having no oxygen demand of its own would eliminate this effect and the resulting errors in computed BOD's. However, in low-flow augmentation, dilution of wastes is accomplished with upstream river water which, though relatively clean, normally has a measurable BOD. Inasmuch as the results from this phenomenon were indistinguishable from the effects of toxicity by means of the normal BOD technique, a means was sought to identify one or the other.

Akerlindh (1953) discussed the phenomenon of higher dilution-water BOD's in incubated mixtures than in dilution-water blanks without reference to toxicity. He proposed formulas which would provide a means of eliminating the error of too-low BOD in the dilution water blank. The formulas are:

$$L_w = \frac{n_2 n_1 (D_1 - D_2)}{n_2 - n_1} \qquad (13)$$

and

$$L_b = \frac{n_2 D_2 - n_1 D_1}{n_2 - n_1} \qquad (14)$$

in which L_w = the BOD of the waste;
L_b = the BOD of the diluting water;
D_1 and D_2 = determined oxygen depletions of two different dilutions of the sample; and
n_1 and n_2 = corresponding dilution factors (the reciprocals of the concentrations of the samples in the diluted mixtures).

With these equations, the incubation of the blank may be eliminated; the BOD of the waste sample can be calculated from equation 13 and the BOD of the dilution water exerted in the mixture can be calculated from equation 14. In the absence of toxicity effects, the Akerlindh formulas applied to several different pairs of incubated dilutions should yield the same BOD for the sample from each pair. Thus a check for toxicity is available which eliminates the interference of the synergistic effect on the dilution-water BOD.

One restrictive qualification of the Akerlindh formulas renders them of little value in low-flow augmentation studies. The equations apply only to very high dilutions far beyond the range of dilution factors normally involved in waste dilution by stream-flow augmentation. For this reason, a pair of more general formulas applying to any range of dilution factors has been derived for use in low-flow regulation studies. The formulas are

$$Y_s = Y_{m1}\frac{(1-P_2)}{(P_1-P_2)} - Y_{m2}\left[\frac{(1-P_2)}{(P_1-P_2)} - 1\right] \qquad (15)$$

and

$$Y_d = Y_{m2}\left(\frac{P_1}{P_1-P_2}\right) - Y_{m1}\left(\frac{P_1}{P_1-P_2} - 1\right) \qquad (16)$$

in which Y_s = BOD of the sample;
Y_d = BOD of the dilution water;
Y_{m1} = BOD of more concentrated mixture incubated;
Y_{m2} = BOD of less concentrated mixture incubated; and
P_1 and P_2 = the concentrations of sample in the more concentrated mixture and in the less concentrated mixture, respectively, expressed as decimals.

Equations 15 and 16 have been used successfully to show the absence of any toxicity effect in a sample of polluted river water after analysis of the BOD data by the standard dilution-water-blank technique (A.P.H.A., 1955) indicating increasing BOD with increasing dilution. The procedure using equations 15 and 16 has been named the "two-dilution method" of BOD analysis to distinguish it from the Standard "dilution-blank method." A separate paper detailing the derivation and use of the two-dilution formulas is in the early stages of preparation.

SUMMARY

During the first two years of the Project, various aspects of low-flow augmentation have been investigated. The legal aspects studied have included public water policy as it affects the development of water resources for the purpose of waste dilution and assimilation.

Economic phases of the study have included a survey of stream-flow design criteria used for the purpose of prescribing waste-treatment requirements. An economic study of the relatively new developments in waste control, sewage oxidation ponds for municipal wastes and holding lagoons for industrial wastes, was undertaken to develop information and procedures necessary for the analysis of these methods as potentially more economical than low-flow augmentation.

Most of the efforts of the project have been applied to the technical problems of low-flow augmentation. Emphasis has been placed on the relationship between organic pollution and stream-flow rate. The approach has

been based on the Streeter-Phelps oxygen-sag formula. The various modifications of the original formula have been reviewed in connection with their applicability to low-flow augmentation problems. Two new formulas have been derived. The first is a simplified formula for the determination of the self-purification coefficient, f, at the critical sag point. The second is a simplification of the original Streeter-Phelps formula for the oxygen deficit, applied to the critical sag point. In the simplified formula, the time-of-flow and k_1 are eliminated, thus reducing the time and work required in field and office studies of the oxygen sag in low-flow regulation problems. A pair of formulas has been derived for the analysis of BOD dilutions in the range of dilution ratios involved in low-flow augmentation. They can be used to resolve the two synergistic effects caused by dilution, the effect of toxicity dilution and the effect of seeding the dilution water with the active biota of a polluted stream (Theriault-Hommon effect).

The following reports have been prepared, or are in preparation:

ANON.
1959 Low Flow Augmentation for Water Pollution Control. (Sanitary Engineering Division News Item) Proceedings, American Society of Civil Engineers, 85, SA2, Part 2, 7 (March).

CARBAUGH, H. C.
1959 A Review of Literature on the Effect of Temperature on the Atmospheric Reoxygenation Rate in Streams. Memorandum Report, Low-Flow Augmentation Project, Department of Sanitary Engineering and Water Resources, The Johns Hopkins University, Baltimore, Maryland (July). (8)

(In preparation) Rapid Solution of the Simplified Oxygen Sag Equation. Low Flow Augmentation Project, Department of Sanitary Engineering and Water Resources, The Johns Hopkins University, Baltimore, Maryland. (6)

HULL, C. H.
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1959a Bibliography on the Effects of Impoundments of Water Quality. Report No. II, Low-Flow Project, Department of Sanitary Engineering and Water Resources, The Johns Hopkins University, Baltimore, Maryland (April). (9)

1959b Bibliography on Biochemical Oxygen Demand. Report No. V, Low-Flow Augmentation Project, Department of Sanitary Engineering and Water Resources, The Johns Hopkins University, Baltimore, Maryland (July). (2) This we have

HULL, C. H. J.
(In Press) Simplified Technique for the Determination of the Self-Purification Coefficient in a Stream. Report No. III, Low-Flow Augmentation Project, Department of Sanitary Engineering and Water Resources, The Johns Hopkins University, Baltimore, Maryland.

(4) Time we have

(In Preparation) Simplification of the Oxygen Sag Equation. Report No. IV, Low-Flow Augmentation Project, Department of Sanitary Engineering and Water Resources, The Johns Hopkins University, Baltimore, Maryland. (5)

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PLANS FOR FUTURE WORK

Objectives for the immediate future include the preparation and publication of detailed reports presenting the findings outlined in this report. Further studies of water resources policy in the States are planned as a continuation of the legal-aspects investigation. Further work on methods of economically evaluating and comparing waste lagooning and low-flow augmentation is already under way. Further testing of the formulas derived for oxygen-sag analysis and BOD analysis is also contemplated.

More distant objectives include the development of improved methods of predicting the effects of impoundments on the quality of water discharged from the dilution of wastes. Another objective is to determine more reliable methods for transposing stream observations of oxygen balance from one season to another, taking into account the changes in temperature and other factors, including those controlling photosynthetic oxygenation.

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Appendix

Stream-Flow Criteria For Design of Waste-Treatment Facilities

State of Mississippi

The Mississippi State Board of Health has not set any specific stream-flow criteria for use in design of pollution-abatement facilities. In some cases the Board has used the minimum flow of record as a basis for design. However, it has been found in many cases that requirements based on minimum stream flow are of little value because the streams in Mississippi, for the most part, fall into two general categories: (1) those that have plenty of water the year round, and (2) those that are completely dry during the summer and fall. Unfortunately, there are no records for most small streams which have year-round sustained flow.*

In 1956 the Mississippi legislature enacted a water-rights law which provided for the appropriation of water from any stream in excess of the "established average minimum flow." The law states:

> "When reasonably required for the purposes of this act, the board shall determine and establish the average minimum flow of a given stream at a given point thereon. The 'average minimum flow as used in this act shall be the average of the minimum daily flow occurring during each of the five (5) lowest years in the period of the preceding twenty (20) consecutive years. Such determinations shall be based upon available stream-flow data, supple-

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* Summary of letter dated January 15, 1958 from R. A. Gerber, Assistant Engineer, Mississippi State Board of Health.

mented, when available data is incomplete, by reasonable calculations."*

The law also states that:

"No appropriation of water shall be authorized that will impair the effect of stream standards set under the pollution control laws of this state based upon a minimum average stream flow."**

Taken together, the two quoted portions of the law appear to provide a fairly definite criterion for the stream flow to be used for design of waste-treatment works or other pollution-abatement facilities. A design flow in excess of the "established average minimum flow" would not be reasonable inasmuch as the excess could be appropriated for other beneficial uses. Since appropriated water may be consumed or diverted from a stream, any excess flow above the established average minimum flow would not be dependable for design purposes.

The Mississippi water rights law, though it provides a criterion for the upper limit of the design flow, does not necessarily guarantee that sources of pollution will be able to design waste-control facilities on the basis of a stream flow as great as the established average minimum flow. The pollution control agency may decide that the water uses other than waste disposal would not be adequately protected by a waste-treatment plant designed on the basis of the "established average minimum flow," and therefore a design flow less than the legally defined low flow should be used for pollution control purposes. However, the established average minimum

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* Chapter 167, Section 2 (i), Mississippi Laws of 1956.

** Chapter 167, Section 4 (d), Mississippi Laws of 1956.

flow as defined in the law would generally serve as a first approximation of the stream flow to be used for design purposes.